P/N InP HOMOJUNCTION SOLAR CELLS BY LPE AND MOCVD TECHNIQUES*

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P/N InP homojunction solar cells have been prepared by using both Liquid Phase Epitaxy (LPE) and Metalorganic Chemical Vapor Deposition (MOCVD) growth techniques. A heavily doped p-$In_{0.53}Ga_{0.47}As$ contacting layer was incorporated in the cell structure to improve the fill factor and to eliminate surface spiking at the front surface. The best conversion efficiencies (total area) obtained under AM 1 illumination are 14.2% for a LPE cell and 15.4% for a MOCVD cell.

INTRODUCTION

Indium phosphide (InP) has recently emerged as an attractive solar cell material for space application, owing to the high conversion efficiencies (ref. 1) and radiation resistance (ref. 2) which were demonstrated in the past few years.

Most of the InP homojunction solar cells reported so far consist of a shallow homojunction. In order to obtain low contact resistance as well as low sheet resistance, the top layer was usually doped heavily; as a result, the minority-carrier diffusion length in this region is very short. To maximize the short-circuit current, the top layer has to be made very thin; however, the reverse saturation current and the diode's ideality factor of InP homojunction solar cells were observed to increase markedly when the p-n junction depth is less than 0.15 µm (ref. 3). Also, the surface spiking at the surface layer of shallow junction solar cells can sometimes cause the deterioration of diode characteristics (ref. 4). To circumvent these problems associated with shallow homojunction cells, we have modified the conventional InP homojunction solar cells by adding an additional contacting $In_{0.53}Ga_{0.47}As$ layer between the front grid contact and the thin top InP layer (This is an extension of our previous work (ref. 5), in which an InGaAsP layer was used as contacting layer). The advantages of this extra InGaAs contacting layer are twofold: firstly, the bandgap of $In_{0.53}Ga_{0.47}As$ (0.75 eV) is much smaller than that of InP (1.35 eV) at room temperature, so

it can be doped more heavily to facilitate the contacting processes. Secondly, the front grid contact is now in direct contact with the InGaAs layer instead of the InP surface layer, thus it eliminates possible surface spiking problems. In the following sections, we present the experimental details of the fabrication and characterization of this type of P/N InP homojunction solar cell prepared by LPE and MOCVD techniques.

EPITAXIAL GROWTH AND CELL FABRICATION

A schematic diagram of the cross section of a mesa-type P/N InP homojunction solar cell is shown in Figure 1. The cell contains an InP p-n junction and an InGaAs contacting layer. To eliminate optical absorption in the InGaAs layer, major portion of the InGaAs layer, which was not covered by the front grid contact, was etched away chemically. The two InP layers and the InGaAs layer were grown successively on a (100) oriented, n^+-InP single crystal substrate with a typical carrier concentration of 2×10^{18} cm^{-3} by either LPE or MOCVD growth techniques.

The LPE growth was performed using a conventional horizontal LPE system. Three epitaxial layers were grown successively on a n^+-InP substrate. An undoped n-type InP layer about 3 to 5 μm thick was grown first on the substrate, which was followed by a p-InP layer and a p^+-InGaAs layer. Zinc was used as p-type dopants for the second and the third epitaxial layers. For the samples we have prepared so far, the two p-type layers have typical thickness values of 0.5 μm. The LPE layers were grown by a supercooling growth technique with a cooling rate of 1°C/min. The growth temperature ranged from 650°C to 620°C. To suppress surface dissociation at the InP substrate surface, the substrate was covered by an InP cover piece during the saturation period, prior to the growth cycle.

The MOCVD wafer was grown in a horizontal atmospheric MOCVD system featuring a fast switching run-vent manifold, allowing for very abrupt interfaces. Trimethylindium (TMI) and trimethylgallium (TMG) were used as group III sources while pure arsine and phosphine were used as group V sources. Hydrogen sulfide (H_2S) and triethylzinc (TEZ) were used as n- and p-type dopant sources respectively. The growth temperature was around 625°C with a growth rate of 5 Å/sec for InP and a growth rate of 10 Å/sec for InGaAs. The background concentrations were about 5×10^{15} cm^{-3} for InP layers and 2×10^{15} cm^{-3} for InGaAs layers.

The layer thicknesses and p-n junction locations for several grown wafers were determined by using a scanning electron microscope. Figure 2 shows the electron-beam induced current (EBIC) signals superimposed on the secondary emission images for the cleaved and stained cross sections of a LPE sample (Fig. 2a) and a MOCVD sample (Fig. 2b). The gentle slopes of the EBIC signals in the lightly doped InP layers indicate that the minority carrier diffusion lengths in this region, which are estimated to be several microns long for both samples, are much longer than the minority carrier diffusion lengths in other layers as expected. The typical carrier

concentrations of the grown layers for the LPE samples are 3.5×10^{18} cm^{-3}, 4.0×10^{17} cm^{-3}, and 4.0×10^{16} cm^{-3} for p$^+$-InGaAs, p-InP, and n-InP layers, respectively; while those for the MOCVD samples are 10^{18} cm^{-3}, 10^{18} cm^{-3}, and 10^{16} cm^{-3} for p$^+$-InGaAs, p-InP, and n-InP layers, rspectively.

The ohmic contacts to the backside were obtained by thermal evaporation of Au/Sn alloy onto the entire substrate, while the front grid contacts were achieved by first evaporating Au/Zn alloy onto the front surface which was previously coated with photoresist and patterned by conventional photolithographic techniques. A subsequent lift-off process completed the deposition of the front contact. The cells were subsequently annealed at 250°C for 1 minute in a flowing nitrogen atmosphere. The contact grids are 50 µm wide and the spacings between the grid lines are 450 µm. The front contact for these cells covers about 12.5 percent of the whole surface. The cell area was defined photolithographically and the cells were made into mesa-type devices by etching the edges of the cells with 1N $K_2Cr_2O_7$: HBr : CH_3COOH (1 : 1 : 1 by volume). The surface area of InGaAs layer, which was not covered by the grid contact, was later removed by selective etching. The frontside of the cells were then covered with 650 A vacuum-deposited Sb_2O_3 as an antireflection (AR) coating. The photograph of the frontside of a completed cell processed from a MOCVD sample is shown in Figure 3. The total cell area for the MOCVD cells is 25 mm^2 while that for the LPE cells, which is 4 mm^2, is somewhat smaller.

DEVICE CHARACTERIZATION

The dark current density - voltage (J-V) characteristics under forward bias for two solar cells prepared by both LPE and MOCVD are shown in Figure 4. The diode's ideality factors are about 1.7 for both cells. The reverse saturation current densities are 3.97×10^{-11} A/cm^2 for the LPE cell and 1.67×10^{-11} A/cm^2 for the MOCVD cell.

The completed cells were tested under simulated sunlight using ELH lamp as light sources. The incident power density was adjusted to 100 mW/cm^2 using a calibrated silicon solar cell. The photovoltaic characteristics of six InP homojunction solar cells prepared from one LPE wafer are summarized in Table I. The average values for V_{oc}, J_{sc}, and FF are 0.812 volt, 25.0 mA/cm^2, and 0.63, respectively. In Table II, we list the photovoltaic characteristics of InP homojunction solar cells processed from one MOCVD wafer. The average values for V_{oc}, J_{sc}, and FF are 0.840 volt, 22.5 mA/cm^2, and 0.72, respectively. The highest conversion efficiencies (total area) achieved are 14.2% for a LPE cell and 15.4% for a MOCVD cell. Figure 5 shows the J-V characteristics under illumination of the best LPE cell and the best MOCVD cell.

The spectral responses for these cells were characterized by using a grating monochromator equipped with a calibrated tungsten light source. The spectral responses of a representative LPE cell and a representative MOCVD cell with and without AR coating are shown in Figure 6. For those uncoated

cells, the spectral response curves exhibit a peak at 0.9 μm, and then drop gradually as the wavelength decreases. The spectral response curves of those coated cells exhibit a flat zone for photon wavelengths between 0.6 and 0.9 μm, and drop off for wavelengths less than 0.6 μm. The overall efficiencies for our cells were improved more than 30% with the aid of an AR coating.

DISCUSSION AND CONCLUSION

Although the open-circuit voltages for our cells are excellent, the short-circuit current values are less than satisfactory. We believe that short-circuit current can be improved by optimizing the cell parameters such as layer thicknesses and doping levels of the epitaxial layers. A larger fill factor can also be expected by increasing the doping level of the InGaAs layer. We have observed very good yield for cells processed from grown wafers prepared by both LPE and MOCVD techniques. However, solar cells processed from MOCVD wafers exhibit better yield and uniformity regarding overall device performance. The preliminary experimental results we obtained from these modified P/N InP homojunction solar cells are encouraging. Such a structure can be easily extented to N/P InP homojunction solar cells. The technical advantages it offers may make it more suitable for large-scale production than the conventional shallow homojunction InP solar cells.

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Table I. Photovoltaic characteristics for InP homojunction solar cells prepared by LPE (AM1, 100 mW/cm^2 at 27°C).

Cell no.	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	Efficiency (%)
1	0.817	25.4	68.0	14.1
2	0.818	25.1	59.2	12.1
3	0.817	24.1	60.5	11.9
4	0.815	25.5	68.2	14.2
5	0.805	24.6	61.9	12.3
6	0.800	24.9	62.1	12.4

Table II. Photovoltaic characteristics for InP homojunction solar cells prepared by MOCVD (AM1, 100 mW/cm^2 at 27°C).

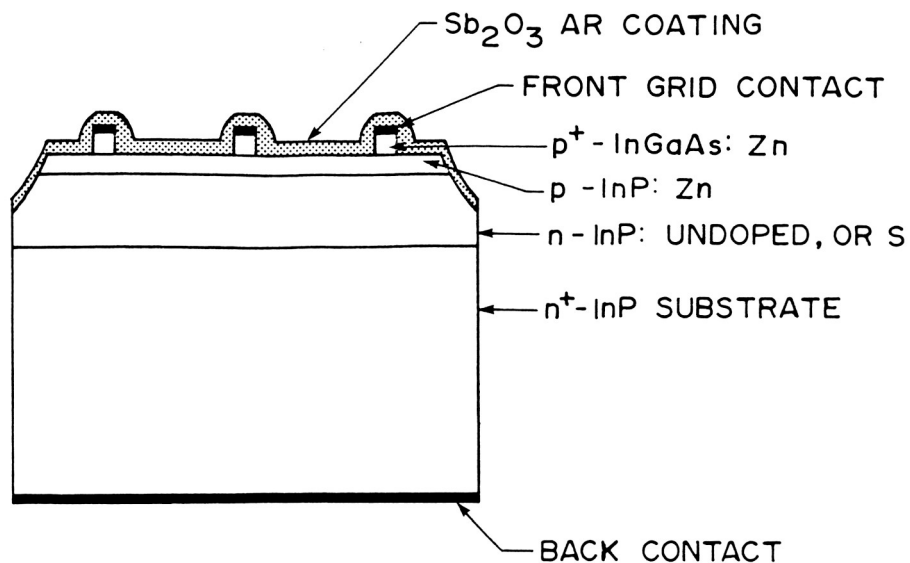| Cell no.	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	Efficiency (%)
1	0.832	21.9	70.4	12.9
2	0.840	21.6	77.9	14.1
3	0.845	22.6	69.4	13.3
4	0.849	22.7	79.7	15.4
5	0.840	22.8	76.5	14.7
6	0.844	22.2	76.6	14.4
7	0.837	22.7	68.9	13.1
8	0.840	23.8	63.8	12.8
9	0.832	23.0	72.0	13.8
10	0.839	21.7	66.8	12.1

Figure 1. Schematic diagram of the cross section of
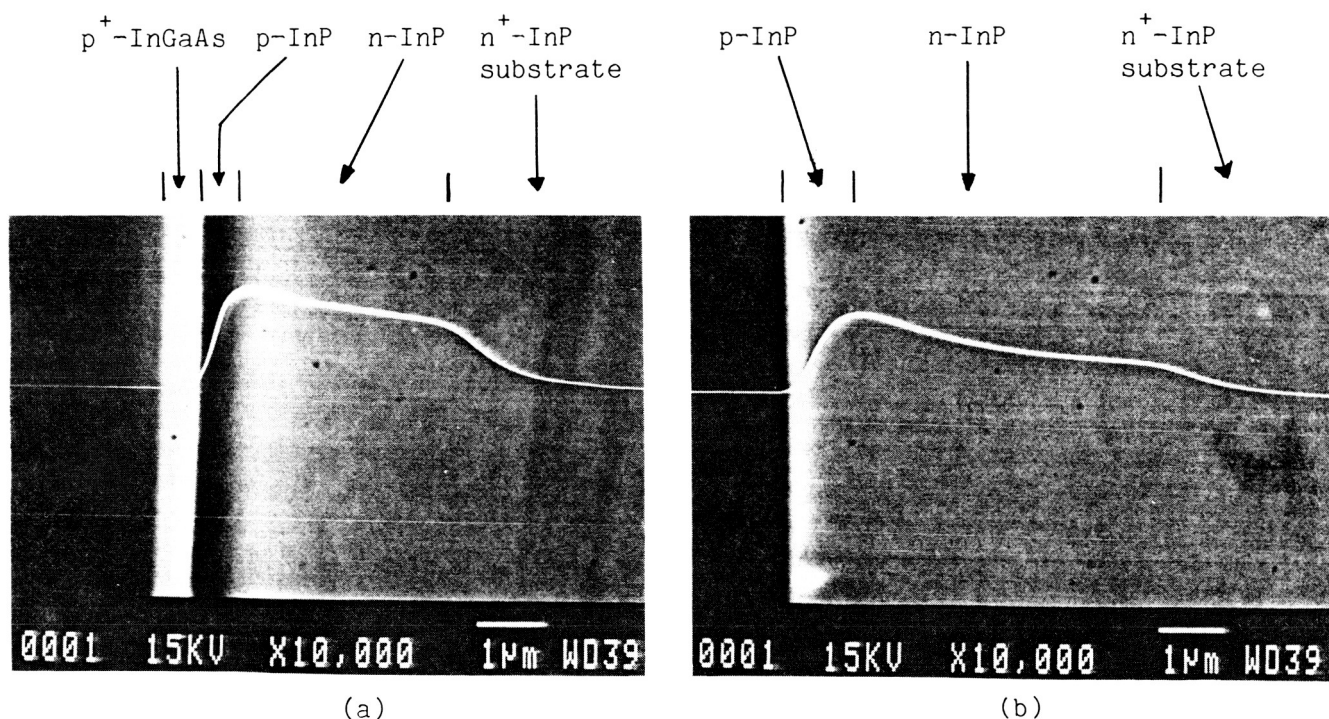a P/N InP homojunction solar cell.

(a)   (b)

Figure 2. Secondary emission and EBIC images of the cross sections of
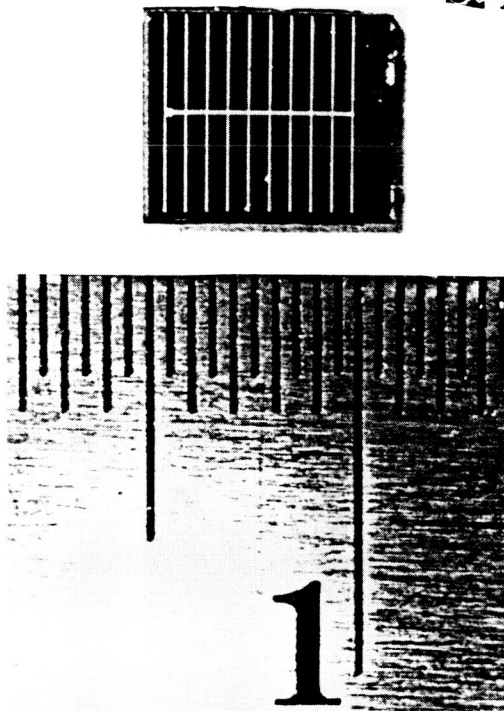two P/N InP solar cells prepared by (a) LPE and (b) MOCVD.

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Figure 3. Photograph of the front side of a completed P/N InP homojunction solar cell.

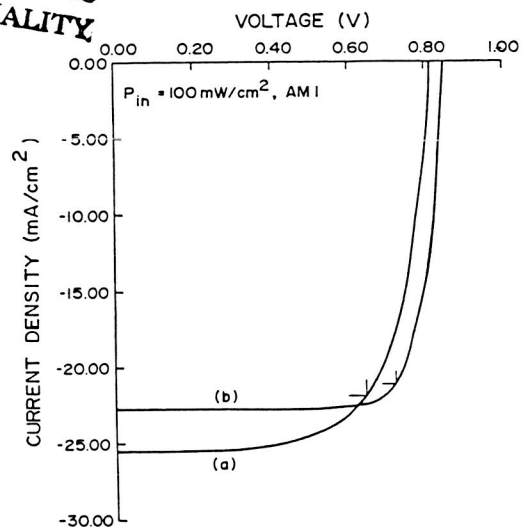Figure 5. Current density versus voltage plot for two P/N InP homojunction solar cells prepared by (a) LPE and (b) MOCVD under AM 1 illumination. The conversion efficiencies for cells (a) and (b) are 14.2% and 15.4%, respectively.
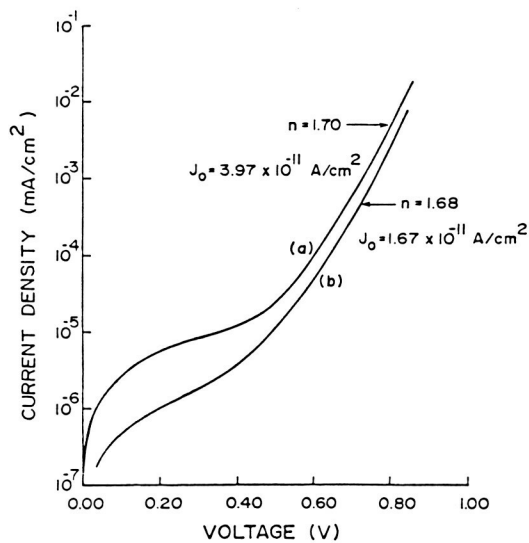

Figure 4. Dark current density versus voltage plot under forward bias for two P/N InP homojunction solar cells prepared by (a) LPE and (b) MOCVD.
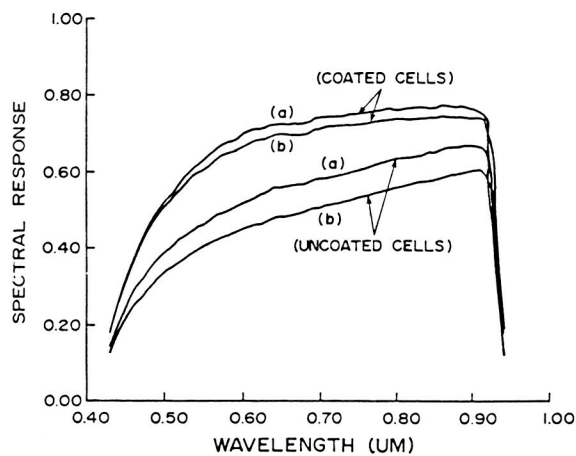

Figure 6. Spectral responses of two typical P/N InP homojunction solar cells prepared by (a) LPE and (b) MOCVD with and without AR coating.

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